# REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188



1. AGENCY USE ONLY ( Leave Blank)

2. REPORT DATE
May 7,1999

3. REPORT TYPE AND DATES COVERED
~~Final report: 9/16/1994 - 3/15/1999~~

4. TITLE AND SUBTITLE
Cyclostationary Signal Processing in Digital Communication Systems

5. FUNDING NUMBERS
DAAH04-94-G-0252

6. AUTHOR(S)
Zhi Ding

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical Engineering
Auburn University
Auburn, AL 36849-5201

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 33151.19-EL-DPS

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Our focus in this ARO research project is to investigate and study the application of cyclostationary signal processing in digital communication systems. We consider several important areas of application including channel equalization, co-channel interference rejection, and antenna beamforming. During this report period, we developed a number of new algorithm for the blind identification and equalization of multiple input multiple output systems. These methods are more robust and accurate than many xisting methods. Blind separation of signals using both the higher order and second order (cyclostationary) statistics are studied. Several simple methods are proposed. We also developed a finite window decorrelator receiver for asynchronous CDMA systems. This new algorithm is near far resistant even when the processing window is rather short, overcoming the weakness of the conventional decorrelator that relies on large (almost infinite) window size. In another important study, we investigate the applicability of blind equalization algorithms in practical wireless cellular systems such as the GSM. Since the GSM transmission is nonlinear and is in burst mode, blind equalization algorithms must be adopted for this nonlinear modulation and must converge within each frame of data burst. Using a linearization method, we simplied the nonlinear GMSK signal into an equivalent linear QAM signal. A de-rotation scheme further allowed channel diversity be extracted without the need of additional downlink antennae. Successful blind equalization and semi-blind equalization results for GSM are established.

14. SUBJECT TERMS
Digital communications, equalization, CDMA, channel identification

15. NUMBER OF PAGES
5

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OR REPORT | 18. SECURITY CLASSIFICATION ON THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

# Final Progress Report

1. *ARO PROPOSAL NUMBER:* P-33151-EL-DPS.
2. *PERIOD COVERED BY REPORT:* January 1, 1998 - December 31, 1998.
3. *TITLE OF PROPOSAL:* Cyclostationary Signal Processing in Digital Communication Systems.
4. *GRANT NUMBER:* DAAH04-94-G-0252.
5. *NAME OF INSTITUTION:* Auburn University.
6. *AUTHOR OF REPORT:* Zhi Ding.
7. *LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:* See reference list.
8. *SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT:*

   Zhi Ding, Associate Professor, Department of Electrical Engineering.

   Ye Li, Graduate Research Assistant (GRA) and Ph.D. candidate, Department of Electrical Engineering.

   Paul D. Burns, GRA and M.S. candidate, Department of Electrical Engineering.

   Zhen Mao, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Junqiang Shen, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Kenneth D. Underwood, GRA and M.S. candidate, Department of Electrical Engineering.

   Todd A. Larabel, GRA and M.S. candidate, Department of Electrical Engineering.

   Gary Li, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Tongtong Li, GRA and M.S. (and Ph.D.) candidate, Department of Electrical Engineering.

   Bin Huang, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Jing Liang, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Bing Chen, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Yi Zhou, GRA and Ph.D. candidate, Department of Electrical Engineering.

   Marcus Lankford, GRA and M.S. candidate, Department of Electrical Engineering.

9. *DEGREES AWARDED DURING THIS REPORTING PERIOD:*

   Ye Li, Ph.D, December 1994.

   Paul D. Burns, M.S. June 1995.

   Kenneth Underwood, Master of Science, January 1997.

   Tongtong Li, Master of Science, June 1998.



## Summary of Accomplishment

- Study of adaptive blind equalization algorithms

  Toward our specific task of developing an adaptive and globally convergent blind equalization algorithm based on second order cyclic and higher order statistics, we analyzed and presented the first known proof of global convergence for the Godard algorithm operating on a blind fractionally spaced equalizer (FSE) [1, 2]. We also presented an adaptive algorithm for channel identification and equalization based on second order cyclic statistics [3]. Furthermore, we also generalized our analysis to the whole class of fractionally spaced adaptive blind equalizers [4, 5] A super-exponential algorithm was also developed for FSE with proven global convergence [6].

- Robust cyclic array signal processing

  We investigated the application of cyclic statistics for multi-sensor array processing. By exploiting multiple sources of cyclic statistical information from the received data, we developed new algorithms in [7] to robustify existing cyclic array processing algorithms by optimizing the use of cyclostationary statistics.

- Improved blind channel identification based on partial information

  We recognized that in most communication systems, the channel consists of a known and an unknown part. Based on this realization, we developed new algorithms in [8, 9] that directly identify the unknown part of the channel based on the known pulse shape. By exploiting the known information, this new approach reduces the computational complexity and improves the accuracy of channel identification. As seen from the improved performance, this is an effective means to exploit the small spectral support of cyclic spectra [10]. This partial information can also be effectively used in designing blind MMSE filter for a specific signal [11]

- Channel identification and multipath equalization for general multiple input and multiple output (MIMO) systems.

  For MIMO systems, we designed an outer-product based robust algorithm for the blind identification of fractionally sampled channels. This algorithm is robust and can largely improve the existing linear prediction based method. It is also easy to implement based on merely the second order statistics of the channel output. We can further accomplish signal separation by exploiting knowledges on the transmitted pulses. For single channel identification, this principle has been presented [12]. For MIMO systems, several newly proposed methods are presented in [13][14][15].

- Efficient and reliable receiver design for CDMA multi-user systems.

  In modern digital communications, asynchronous CDMA system is increasingly becoming the efficient modulation scheme for multi-user separation. We present a method [16] that makes initial decisions on bits for both edges of the finite observed window. These initial decisions are then used to make the subsequent decisions of the whole sequence inside the observed window based on the decorrelating method. We call this as Edge Decision Assisted Decorrelator (EDAD), which is shown to be near-far resistant.

  We also derived [17] a new projection-based blind adaptive multiuser detector is proposed. The proposed detector is motivated by the linearity of multipath interference. We construct a subspace that is orthogonal to the space spanned by the desired signature vector with different possible delays. If the steering vector is in the orthogonal subspace in each step of the adaptive algorithm, there is no cancellation of the desired signal. Better performance is obtained.

- Column anchored ISI cancellation

  We propose a direct blind zeroforcing approach to cancel inter-symbol interference (ISI) in multiple user FIR systems [18, 19]. By selectively anchoring columns of the channel convolution matrix, we present two kinds of column-anchoring zeroforcing equalizers (CAZE). Unlike many known blind identification algorithms, these equalizers do not need an accurate estimate of the channel orders. Exploiting second order statistics (SOS) of the received signals, they can retain a pre-selected block of columns in the channel convolution matrix (the number of columns in a block column equals that of users) and force the remaining columns to zero. They do not rely on and are not sensitive to channel order estimate, as other SOS algorithms do. The algorithm development is very simple and easy to understand. Maximum likelihood equalizer output for single user system is derived. Simulation results show that the CAZE is effective for blind equalization of a single-user linear QAM wireless communication system and even for the GSM mobile communication system.

- Blind signal separation in MIMO systems.

  After blind channel identification, signal separation for particular sources is the next important step. An algebraic principle for signal separation was presented in [20] where a multi-stage methodology is presented that utilizes different higher order statistics (HOS) to separate signals of interest. Rather than fixing the order of HOS for a given algorithm, we derive a small but

sufficient set of statistical equations for multi-stage signal separation. As each stage separates signals into finer and finer categories, signal separation within each small category becomes easier to separate using the next level HOS. For non-white signals such as audio messages and speech, we developed a simple and effective matrix pencil algorithm [21] that only requires the use of second order statistics. So long as signals for separation possess different power spectra, their separation can be accomplished by solving a generalized eigen-value equation involving second order statistics.

- Blind and semi-blind equalization for wireless GSM systems.

  While most published works have focused on the standard model of QAM systems, few have directly attacked the problem of blind equalization in practical wireless communication systems. GSM is one of the most popular digital cellular systems on the world today. Investigating and understanding the feasibility and performance of blind equalization for GSM would have significant impact in the design of future wireless systems.

  In [22][23], we focus on the design of blind equalization receiver for the phase modulated GSM systems without relying on additional antennas. We investigate whether and how the mathematically elegant SOS methods can be applied to the nonlinear modulated GMSK signals. As GMSK signals have almost no excess bandwidth, we are particularly interested in determining whether SOS methods relying on channel diversity can be adapted for the baud-rate sampled channel signal from a lone antenna output. To overcome the first obstacle of nonlinear modulation, we derive an equivalent baseband PAM model for the GMSK signal used in GSM systems. More importantly, to apply SOS methods on single channel output, we use a de-rotation scheme to create two sub-channels for each GMSK signal even though the GMSK signal has almost zero excess bandwidth. To improve the equalization performance, we also developed two semiblind equalization methods [24] that not only rely on the statistical information, but also utilize the available but short midamble training signal in each TDMA burst of the GSM transmission.

## References


[1] Y. Li and Z. Ding, "Global Convergence of Fractionally Spaced Godard Adaptive Equalizers", *Proc. 1994 Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, Oct. 1994.

[2] Y. Li and Z. Ding, "Global Convergence of Fractionally Spaced Godard Adaptive Equalizers," *IEEE Transactions on Signal Processing*, pp.818-826, April 1996.

[3] Z. Ding and R. A. Kennedy, "Algebraic Self-Training Algorithms for Multi-Channel System Identification and Equalization," *Proc. 1994 Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, Oct. 1994.

[4] Zhi Ding, "On Convergence Analysis of Fractionally Spaced Adaptive Blind Equalizers", *Proc. Int. Conf. on Acoustics, Speech, and Signal Processing*, Atlanta, GA, May 1996.

[5] Ye Li, K. J. R. Liu, and Z. Ding, "Length and Cost-Dependent Local Minima of Unconstrained Blind Channel Equalizers", *IEEE Transactions on Signal Processing*, pp.2726-2735, December 1996.

[6] Zhi Ding, "On Convergence Analysis of Fractionally Spaced Adaptive Blind Equalizers", *IEEE Transactions on Signal Processing*, pp. 650-657, March 1997.

[7] Paul Burns and Zhi Ding, "Robustification of Cyclostationary Array Processing Techniques", *Proc. Int. Conf. on Acoustics, Speech, and Signal Processing*, pp. 1589-1592, Detroit, May 1995.

[8] Z. Ding and Z. Mao "Knowledge Based Identification of Fractionally Sampled Channels", *Proc. 1995 Int. Conf. on Acoustics, Speech, and Signal Processing*, pp.1996-1999, Detroit, MI, 1995.

[9] Zhi Ding, "Myopic Channel Identification: Identifying unknown Channels based on known pulse shapes", *Proc. 1995 IEEE Global Telecommunications Conference*, Nov. 1995.

[10] Z. Ding, "Multipath Channel Identification Based on Partial System Information", *IEEE Transactions on Signal Processing*, pp. 235-241, Jan. 1997.

[11] Zhi Ding, "Blind Wiener Filter Estimation for Multi-Channel Systems Base on Partial Information," *Proc. 1997 IEEE International Conf. on Acoustics, Speech, and Signal Processing*, pp.2521-2524, April 1997.

[12] Zhi Ding, "An Outer-Product Decomposition Method For Blind Channel Identification", *Proc. 1996 International Communications Conference*, pp.852-856, Dallas, 1996.

[13] Zhi Ding, "Matrix Outer-product Decomposition Method for Blind Multiple Channel Identification," *IEEE Trans. on Signal Processing*, 45(12), pp. 3053-3061, 1997.

[14] Zhi Ding, Iain Collings, Ruey-wen Liu, "A New Blind Zeroforcing Equalizer for Multichannel Systems", *Proc. 1998 IEEE International Conf. on Acoustics, Speech, and Signal Processing*, pp.3177-3180, Seattle, May 12, 1998.

[15] Junqiang Shen and Zhi Ding, "Zero-Forcing Blind Equalization Based on Channel Subspace Estimates for Multiuser Systems", *Proc. Int. Conf. on Acoustics, Speech, and Signal Processing*, May 1999.

[16] J. Shen and Z. Ding, "Edge Decision Assisted Decorrelators for Asynchronous CDMA Channels", *IEEE Transactions on Communications*, pp.438-445, March 1999.

[17] J. Shen and Z. Ding, "Blind Adaptive Multiuser CDMA Detection Based on a Linear Projection Constraint", *Proc 1st IEEE Workshop on Signal Processing Advances in Wireless Communications*, pp.261-264, April 1997, Paris.

[18] Jie Zhu, Xi-Ren Cao, Zhi Ding, and Junqiang Shen, "A Blind Inter-symbol Interference Cancelation Method for Multi-user Systems with Channel Diversity", *Proc. Asilomar Conf. on Signals, Systems, and Computers*, pp.565-569, Pacific Grove, 1997.

[19] Jie Zhu, Zhi Ding and Xi-Ren Cao, "Column Anchored Zeroforcing Blind Equalization for Multiuser Wireless FIR Channels", *IEEE Journal on Selected Areas in Communications*, pp.411-423, March 1999.

[20] J. Zhu, X.-R. Cao and Z. Ding, "An Algebraic Principle for Blind Separation of White Non-gaussian Sources", to appear in *Signal Processing*, August 1999.

[21] Chunqi Chang, Zhi Ding, Mark S.-F. Yau, and Francis H. Y. Chan, "A Matrix-Pencil Approach to Blind Separation of Non-White Signals in White Noise", *Proc. 1998 IEEE International Conf. on Acoustics, Speech, and Signal Processing*, pp.2485-2488, Seattle, May 12, 1998.

[22] Ge Li and Zhi Ding, "Single Channel Linear Blind Equalization for GSM Cellular Systems", *Proc. 1998 IEEE International Conf. on Communications*, Atlanta, June, 1998.

[23] Zhi Ding and Ge Li, "Single Channel Blind Equalization for GSM Cellular Systems", *IEEE Journal on Selected Areas of Communications*, vol.16, pp.1493-1505, October 1998.

[24] Ge Li and Zhi Ding, "Semi-Blind Channel Identification Used in GSM System," *Proc. 1998 IEEE International Conf. on Acoustics, Speech, and Signal Processing*, pp.3389-3392, Seattle, May 12, 1998.

[25] Z. Ding, "Characteristics of Band-limited Channels Un-identifiable from Second Order Cyclostationary Statistics" *IEEE Signal Processing Letters*, pp.150-152, May 1996.

[26] Rodney A. Kennedy, Deva K. Borah, and Zhi Ding, "Discretization Issues for the Design of Optimal Blind Algorithms",*Proc. 1997 IEEE International Conf. on Acoustics, Speech, and Signal Processing*, pp.51-54, April 1997.

[27] Raul A. Casas, C. Richard Johnson Jr., Rodney A. Kennedy, Zhi Ding, and Roberto Malamut, "Blind Adaptive Decision Feedback Equalization: A Class of Channels Resulting in Ill-convergence from A Zero Initialization", *Int. Journal of Adaptive Control and Signal Processing*, vol.12, pp. 173-193, March 1998. March 1998.

[28] Tuan Nguyen and Zhi Ding, "Blind CMA Beamforming For Narrowband Signals with Multipath Arrivals", *Int. Journal of Adaptive Control and Signal Processing*, vol.12, pp. 157-172, March 1998.

[29] Darren B. Ward, Zhi Ding, and Rodney A. Kennedy, "DOA Estimation for Broadband Signals Using Frequency Invariant Beamforming", *IEEE Transactions on Signal Processing*, 46(3), pp. 1463-1469, May 1998.

[30] Z. Ding, "Adaptive Filters for Blind Equalization" *IEEE DSP Handbook*, §24, Douglas B. Williams, Ed., IEEE Press, 1998.

[31] Zhi Ding and Tuan Nguyen, "Signal Separation and Extraction via Kurtosis Maximization", *Proc. IEEE Workshop on Digital Signal Processing*, Bryce Canyon, August 1998.

[32] Z. Mao and Zhi Ding, "A Non-parametric Phase Estimation Method for SIMO Systems based on Second Order and Higher Order Statistics," *IEEE Trans. on Signal Processing*, pp. 843-847, March 1999.

[33] Tongtong Li and Zhi Ding, "Joint Transmitter-Receiver Optimization for Non-maximally Decimated Filterbank Precoding Systems", to appear in *IEEE Transactions on Signal Processing*, May 1999.